

A New Hypothesis for Layers of High Reflectivity Seen in MST Radar Observations

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We have worked with MST Radar located at Gadanki, Tirupati, India(13.47 degree N, 79.18 degree E). Altitude of the location is approximately 100 meters. This is the first and only MST Radar operating in India. It is in Tropical Monsoon region. Monsoon moves northward across Tirupati around 1st June and withdraws southward across Tirupati in the first week of December. Our interest has been to examine the characteristics of vertical velocity and other wind characteristics associated with monsoon. We examined the characteristics of range-compensated Signal-to-Noise ratio (r^2 SNR). We call this as Reflectivity. We examined the MST Radar data set for 14 months (September 1995 to November 1996 except May 1996). The height range considered for the analysis was between 3.6 km and 21 km above ground. Our findings have been on the following lines:

1) Except on Thunderstorm occasions, high reflectivity-regions are in the form of layers 1-2 km thick. One such high-reflectivity layer is always present near tropopause level 17 km. Below the tropopause, there is a bunch of such high-reflectivity layers, generally 3-4 in number, between 4 and 11 km. The atmospheric layer between 11 and 15 km is generally free from high reflectivity layer.

2) On a thunderstorm occasion, there is a deep high-reflectivity layer extending from 4-11 km. After the passage of the thunderstorm, this deep layer of high reflectivity breaks up into layers.

3) Layers of high reflectivity occur throughout the year even outside monsoon season, when ITCZ is far away from the region and they cannot be attributed as originating from deep convective clouds. When visual observation and MST observations are taken simultaneously at Gadanki, visual clouds are estimated to be at the same levels as the high reflectivity layers seen through MST observations. Indian satellite pictures over Gadanki also suggest similar heights of clouds as given by MST Radar for high reflectivity layers.

4) Satellite pictures in infra-red range show much more extensive areas of cloudiness than the pictures in the satellite visible range. In other words, there are extensive sub-visual clouds in the atmosphere.

5) Every month early morning and late evening, in twilight hours we see beautiful cirrus clouds in the form of cloud streets, streaks or sheets on several occasions which may or may not be clearly visible at other hours.

6) On looking at the sky frequently, one gets the impression that the sky is not clear even though we do not see clouds or haze layers. In these haze layers, appear clouds in the form of cloud streets, streaks or cloud sheets at some times. The appearance of these clouds gives the clear impression that there are waves in the atmosphere which give visible clouds in the region of upward motion associated with these waves. Again in each bigger wave cloud, there are smaller and smaller wave clouds and clearances; there are waves within waves. When the clouds disappear, they leave a sort of haze. Hence, the clouds form out of haze and leave some haze after dissipating. Even when there are no visible clouds during the day or night, the structure of the atmosphere is patchy in appearance. One gets a clear impression that there are waves and waves, bigger and smaller waves in the atmosphere which are creating patches of haze and sometimes visible clouds in the atmosphere. These are due to gravity-type waves with a very wide spectrum of horizontal and vertical wavelengths. As we know from theoretical and observational evidence, horizontal wavelengths are 1-2 orders of magnitude larger than vertical wavelengths. If and when they occur in the atmosphere, they have a tendency to take horizontally spread layered structure with vertical depth 1-2 orders of magnitude smaller than horizontal extent.

7) In the atmosphere, we visualize three classes of waves: a. Inertial waves or Rossby-type waves: Their horizontal extent is of the order of a few thousand kilometers and vertical wavelengths of the order of 10 km. In the mechanism of their formation, we have to consider the rotation of the earth and the resulting coriolis force. Their period is of the order of a few days. b. Gravity waves: These arise mainly from local horizontal pressure gradients arising out of gravitational weight of the overlying air column, air accelerating from higher pressure towards lower pressure. Horizontal accelerations and displacements are accompanied by appropriate vertical accelerations and displacements to conform to the requirements of law of conservation of mass i.e., equation of continuity.

Vertical displacements and accelerations of air parcels can also arise from buoyancy forces. Heavier parcel tends to sink down while lighter air parcels tend to rise up in an environment of horizontal density gradients. These are called Brunt-Vaisala oscillations. These horizontal gradients of density arise out of differences in temperature, humidity and hydro-meteor loading.

This hydrometeor-loading needs a little elaboration:

(i) Every parcel of cloud air contains at least one hydrometeor in liquid water or solid form. Inside each hydrometeor is an aerosol which acts as a nucleus which has induced condensation and/or freezing.

(ii) Invariably, hydrometeor has higher density than the surrounding air. As such, it tends to fall down due to gravitational force.

(iii) As it descends down, it exchanges sensible heat and moisture with its environment. Hence, its volume, mass, and density undergo a change during its descent.

(iv) As the hydrometeor descends down with gravitational acceleration through the air parcel, there is frictional resistance/viscous resistance to its vertical motion. soon, the hydrometeor loses its acceleration and descends down with what is called "Terminal velocity". Where has its weight gone? Its weight is taken up by the air parcel which is offering resistance to its vertical movement and acceleration. In other words, the air parcel becomes heavier to the extent it has taken over the gravitational acceleration of the falling hydrometeor. If the hydrometeor falls with its terminal velocity, it means that its entire weight is taken over by the air parcel. As such the air parcel has become heavier by the total weight of the hydrometeor; the density of the air parcel has effectively increased.

If only half of the gravitational acceleration of the descending hydrometeor has been taken over by the air parcel, then the weight of the air parcel has increased only by half the weight of the hydrometeor.

The hydrometeor gradually loses its gravitational acceleration and gives its weight to the surrounding air parcel gradually and not instantaneously. As such, the air parcel takes the load of the hydrometeor gradually during the downward trajectory of the descending hydrometeor.

In many calculations, for the sake of simplicity, it is assumed that as soon as condensation or freezing takes place in the atmosphere, the load of the hydrometeors is immediately taken over by the surrounding air. However, we have to recognize that the hydrometeor-loading occurs gradually through a finite interval of time.

We should also remember that during the fall, the hydrometeor is simultaneously undergoing a change in its volume, mass and density. Hence, a realistic, quantitative estimate of hydrometeor loading effect on the air parcel needs careful calculation. However, nature takes care of the process and creates varying density effects on the cloud air parcel as the hydrometeor descends.

(v) In addition to buoyancy fall of the hydrometeor, there are upward and downward motions of air parcels inside the cloud. These upward and downward motions of air parcels inside the cloud create further complications in the calculation of hydrometeor-loading effect on air parcel.

(vi) In addition to pure buoyancy forces operating in a class of waves called gravity waves, there also occur what are known as Kelvin-Helmholtz waves due to presence of vertical shear of horizontal winds which is almost always present.

(vii) This class of gravity waves of Kelvin-Helmholtz type have very small wavelengths of the order of centimeters and meters and correspondingly small periods of the order of a few minutes. Earth's rotation or Coriolis force does not perceptibly come into the calculations for these waves.

c. Inertio-Gravity waves: Between the two extremes of large inertial waves and small gravity waves, there is an intermediate class of waves which may be termed as inertio-gravity waves in which Coriolis force plays some role along with gravity force. There is literature on the subject of inertio-gravity waves (^{1,2,3}, etc.), but more work needs to be done on this class of waves. Orographic influence also come into play.

8) When we fly in an aircraft, large-scale weather and clouds are influenced by Rossby-type waves. When we look at the sky through cockpit or through the window near the window-seat, during day time, we immediately get the view of air clouds at different levels and also gravity waves of various dimensions near the flight level. We see fairly large waves with estimated wavelengths of the order of tens of kilometers, along with embedded smaller and smaller waves, thick clouds, thin clouds, thinner clouds, space filled with haze and space clear of visible clouds.

In our view, MST Radar reflectivity pattern gives us spot view of these numerous beautiful waves.

9) We have analyzed the field of MST Radar reflectivity as seen at Gadanki along with MST Radar measured wind fields. We have interpreted the reflectivity fields within a conceptual model given below:

(i) Inertio-gravity waves in the atmosphere generate layers of upward/downward motion, high/low humidity and high/low temperature lapse rates. The layers of upward and downward motion are regularly seen in the vertical wind field given by MST Radar. The vertical wavelength of these inertio-gravity waves has wide spectrum depending on orography and diabatic heating; vertical wavelength of about 5 km is a more frequently observed wavelength. The corresponding horizontal wavelength is of the order of 200 km, the more dominant wavelength visible in satellite picture is 500 km in the direction of wind and 1000 km across the wind.

The layers of high relative humidity created by inertio-gravity waves are favorable for the formation of layered clouds, which we call "Mother Cloud Layers"; these clouds may be visible or sub-visible.

(ii) Hydrometeors inside a "Mother Cloud Layer" tend to fall down attaining their respective terminal velocities. During their stay inside the clouds, the hydrometeors exchange heat, moisture, mass and momentum with the environmental air on small micro-scales. These exchanges between the hydrometeors and the "Mother Clouds's air"

create strong gradients of temperature, humidity, density and momentum. Density variations are also created through hydrometeor-loading.

Electrical charges are also generated during the processes of condensation, evaporation, freezing, melting and sublimation.

These micro-physical gradients in density along with prevailing wind field in the vertical generate internal gravity waves in the form of Brunt-Vaisala oscillations, Kelvin-Helmholtz waves and other waves of different horizontal and vertical wavelengths. These wavelengths range from a few millimeters to tenths of meters in the vertical and from a few meters to about thousand meters in the horizontal. Known laws of physics and dynamics suggest that the wavelengths may be still smaller, equivalent to the distances between adjacent parcels of air exchanging heat moisture, mass and momentum, with the hydrometeor embedded in the parcel.

(iii) The strong gradients of temperature, humidity and density created by these micro-physical and micro-dynamical processes in the air surrounding the hydrometeor or an ensemble of hydrometeors cause strong variations in the refractive index of air parcel, in respect of electro-magnetic lidar and radar beams impinging on the air parcels. In turn, this causes high reflectivity/scatter of the impinging lidar/radar beam. In respect of VHF MST radar Bragg-type reflection/scatter is a dominant type of reflection/ scatter.

We examined the size of air parcels giving the highest values of reflectivity, at Gadanki. We came to the conclusion that their horizontal extent is of the order of 1 km while their vertical extent is of the order of 100 m.

Indian MST radar beam oriented in vertical has a half-wavelength of about 3m. As such, Indian MST radar is capable of detecting reflectivity patterns of vertical wavelengths of the order of about 6m. These small-scale variations in reflectivity appeared in the form of very delicate embroidery inside the large-scale reflectivity of the "Mother Cloud Layer".

(iv) These variations in the reflectivity pattern may look like turbulent fluctuation in the atmosphere. If we do not associate these fluctuations with clouds and hydrometeors inside the clouds, the clouds might appear as clear-air turbulence as has been prevalent in the current explanation appearing in literature connected with MST radars. This prevalent explanation has faced paradoxes, the main paradox being of thin horizontal sheets of turbulence.

If we free our thinking from the concept of clear-air turbulence and turn our thinking in the direction of visible or sub-visible clouds containing hydrometeors, the apparent paradoxes of clear-air turbulence causing high- MST radar reflectivity get immediately resolved.

The existence of sub-visible clouds occupying much larger area than the visible clouds has now been established beyond question, through latest observations by satellites in the infra-red range, by aircraft flying through cirrus cloud air and by lidars operating in high altitude aircraft sending their beams through visible and sub-visible cloud layers.

(v) Using over 2,50,000 observational data points for MST radar reflectivity and vertical wind shear (deduced from corresponding MST radar wind observations) spread over 14 months (from 1995 September to 1996 November), we plotted scatter diagrams of MST radar reflectivity versus vertical wind shear. We are pleasantly surprised to find that reflectivity decreases almost exponentially as vertical wind shear increases. If mechanical turbulence was the main cause of high reflectivity, we should see reflectivity increasing with vertical wind shear, and not decreasing almost exponentially. Scatter diagrams for each of the 14-months are presented in⁴. Also, Scatter diagrams for four representative months (January, April, July and October), for Indian monsoon region, are presented in^{5,6}. This shows that mechanical turbulence is not the principal cause of high-MST radar reflectivity.⁷ had hypothesized that turbulence may not be the primary cause of high-reflectivity seen in MST radars.

(vi) Knowing the importance of cirrus clouds, the world scientific community launched the programme known as FIRE (First ISCCP Regional Experiment). This FIRE programme concentrated on the study of layer clouds (Cirrus Clouds in the upper troposphere and low level stratus clouds in the lower troposphere). FIRE I programme was executed during the period 1985-1990 while FIRE II programme was executed during the period 1990-1995. FIRE III programme is proposed to be executed in the beginning of this new millennium, with particular emphasis on the tropics. Results of FIRE I have been summarized in a special issue of Monthly Weather Review (November, 1990); results of FIRE II have been summarized in a special issue of Journal of Atmospheric Sciences (December, 1995). This topic is an important component of CLIVAR programme in the tropics.

The results of FIRE I and FIRE II have broadly confirmed that there is fine micro structure inside the layered clouds which can be interpreted easily, atleast qualitatively, in terms of micro-physical and micro-dynamical processes presented above.

Also, the latest Numerical Modeling Work on Cirrus Clouds (for example^{8,9,10}) show that there are fine-scale structures of various in-cloud parameters including temperature, humidity and ice-concentrations.

In fact in our view these fine scale structures created inside the visible or sub-visible "Mother Cloud Layers" can cause steep refractive index gradients sufficient to cause high-MST radar reflectivity.

10) We expect that the conceptual model of MST radar reflectivity presented above will give a new orientation to the thinking and interpretation of MST radar reflectivity. It will provide a satisfactory, physically and dynamically acceptable, interpretation of the reflectivity patterns seen in the MST radar observation.

11) A few corollaries follow from this conceptual model:

(i) Since, high-MST radar reflectivity layer, 1-2 km thick, is always observed near the tropopause, it may or may not be directly connected to inertio-gravity waves. The mechanism for the formation and sustenance of high-reflectivity layer is realized as follows:

(a) The temperature near the tropopause level are very cold (200 K); temperature lapse rate is stable, 2-4 degree C/km; as such vertical mixing of air is inhibited and is weak. Relative humidity below the tropopause is high¹¹. Water substance and aerosols injected into the upper troposphere by deep convection near ITCZ remains below the tropopause while the relative humidity is very low above the tropopause. Water substance and aerosols form visible or sub-visible cirrus cloud layer or haze layer below the tropopause. Through the micro-physical and micro-dynamical processes mentioned earlier, the air layer develops strong vertical gradients or discontinuities in the refractive index with respect to MST radar beam impinging on the air there. This gives high-reflectivity echoes near the tropopause level on all days of the year.

When the cloud gets dissolved, it leaves large number of aerosols suspended there. By themselves, aerosols are not likely to be detected by MST radar. But the layer of high content of aerosols can be detected and has been detecting near the tropopause (^{12, 13, 14} etc.).

In the tropics, ITCZ injects aerosols and moisture which remain trapped in the layer immediately below the tropopause. In extra-tropics, this injection is done by extra-tropical cyclone waves and polar front. On the same reasoning, as given for tropics, a layer with high content of aerosols and thin cirrus ice crystals will also get formed below the tropopause in extra-tropics. Thus a layer having high content of aerosols and thin cirrus cloud is expected to envelope the whole earth's atmosphere near tropopause. This has been substantiated by observations of (Nee et al., 1995, 1998; FIRE I and FIRE II observations and their results published in the Special issues of Monthly Weather in November 1990 and Journal of Atmospheric Sciences in December 1995 respectively). Asnani et al.¹⁵ had hypothesized the existence of an aerosol layer near tropical tropopause, based on the same mechanism mentioned above.

(ii) As we have stated above, observations confirm existence of alternate layers of upward and downward motion with vertical depth of 2-3 km. We should expect accumulation and depletion of both water substance and aerosol substance near the levels of vertical convergence. Further vertical upward motion tends to create higher relative humidity and higher temperature lapse rate; vertical downward motion tends to do the opposite, creating stable lapse rate and drier air. Hence we should expect to find layers of high and low relative humidity in the vertical. Sensitive instrumentation is required to detect this type of structure in the atmosphere; this structure is likely to be missed by the ordinary radiosonde instruments. Such layers have been detected by special effort¹⁶.

(iii) As stated earlier, these alternate layers of upward and downward motion are associated with inertio-gravity waves, which are always present in the atmosphere. These vertical wave motion will also tend to split large convective clouds, particularly in their decaying stage, into layered clouds. While convective instability in the atmosphere tends to generate deep convective clouds in the tropical atmosphere, these inertio-gravity waves inhibit the formation and sustenance of these deep convective clouds in the tropical atmosphere.

(iv) Cirrus clouds have a capacity to retain their existence for a long time, even away from the source of their formation. Hence, visible or sub-visible cirrus clouds are likely to be seen at many places, with or without deep convective clouds. The upward vertical motion associated with inertio-gravity waves tends to generate cirrus clouds, visible or sub-visible at many places in the atmosphere. If nothing else, these clouds influence the radiative heat budget of the earth's atmosphere.

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